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U. S. ARMY
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

CRASH INJURY EVALUATION

HELMET DESIGN CRITERIA

Based on the U. S. Army APH-5 Helmet Evaluation

April 1962

Contract DA-44-177-TC-802

TCREC Technical Report 62-57

prepared by :

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FOREWORD

This report was prepared by Aviation Crash Injury Research, a division of the Flight Safety Foundation, Inc., under the terms of Contract DA 44-177-TC-802. Views expressed in the report have not been reviewed or approved by the Department of the Army; however, conclusions and recommendations contained therein are concurred in by this Command.

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Report of Crash Injury Evaluation
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for
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CRASH INJURY EVALUATION

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SUMMARY

Head injury is an exceedingly common occurrence in aircraft accidents. Because of the seriousness of this injury in its production of residual brain damage, death, and disfigurement, it is of paramount importance that all necessary steps be taken in the way of prevention and protection to alleviate the occurrence of these disastrous conditions.

This report provides a discussion of:

1) The problem and significance of head injury in aircraft accidents,

2) The pathology of head injuries,

3) The requirements of protective devices of the head against traumatic injury,

4) The characteristics of the presently employed Army helmet, the APH-5.

5) Injury patterns as they occur in Army accidents relative to specific deficiencies of the APH-5 helmet, and

6) Recommendations and concepts for resolution of the deficiency manifest in the APH-5.

Several accident cases involving the APH-5 are discussed in an appendix.

INTRODUCTION

THE PROBLEM

Head injuries are the most frequent and significant of all injuries experienced in aircraft accidents (References 1, 2, 3, 4). Furthermore, the head is often the only vital part of the body exposed to dangerous injury, and fatality from head injury alone is common.

Man's awareness of the need to protect his head has stimulated extensive research in devising means by which to accomplish the desired protection. Time has provided a long list of devices ranging from a crude capsule around the head to relatively effective energy absorption shields for the skull and its contents. Our present understanding of head injury dictates that the external surface of a head protective device must engage and distribute impact forces over energy absorbing materials so that uniform deceleration of the whole head is achieved at levels that are not injurious for low-force impacts and not lethal for high-force impacts.

Truly, even the crudest of helmet designs offers some protection; and immediately following the institution of protective devices, reduction of head injury was noted. In 1943, in England, it was noted that the wearing of helmets by motorcycle operators resulted in a quartering of the incidence of fractures; and in nonlethal accidents, 50 percent of the persons who did not require hospitalization would have required treatment if a crash helmet had not been worn (Reference 5). In 1954, the USAF reported that from 1 January 1951 to 31 December 1953, in fighter and jet bomber accidents where personnel were provided crash helmets, 14.2 percent of the head injuries received were major and 7.4 percent were fatal. In all other aircraft-type accidents in which personnel had no helmets, 24.3 percent of head injuries were major and 14 percent were fatal (Reference 6). The recent U.S. Army experience as reported by USABAAR in 1961 (Reference 3) indicates that, in 1220 major accidents, of 991 occupants not wearing helmets, 20 percent received major, critical, and fatal head injuries, while of the 268 wearing crash helmets, approximately 11 percent received these same types of injuries.

From the above, it is obvious that even from the beginning, the concept of prevention of head injury through protection has been a sound one. Comparing the 1943 reference with the report in 1961, the major, critical, and fatal rates continue to show only a 50 percent reduction bv use of crash helmets in spite of extensive design sophistication. Several factors are responsible for this consistency, including such variables as increasing overall forces being involved, change in type of aircraft, as well as failure of specific features in the design of the presently used crash helmet (the APH-5).

HEAD INJURY IN AIRCRAFT ACCIDENTS

The head continues to be a major site of injury in current Army aviation, even with improved restraint and protective measures. In a recent study at USABAAR (Reference 10), head injuries in survivable accidents accounted for 23 percent of the injuries received by survivors in fixed-wing accidents and 21.3 percent of the injuries of survivors in rotary-wing accidents. Of those who died in survivable fixed-wing accidents, 31.7 percent of the fatalities were due to head injury; in survivable rotary-wing accidents, 24.2 percent were due to head injury. (These last percentages do not include those deaths due to multiple extreme injury in which, of course, the head might have been included.) These statistics include all injured occupants, with and without headgear.

In a 1952 report (Reference 1) describing the site, frequency, and dangerousness of injury sustained by 800 survivors of light plane accidents, 88 percent sustained injuries to the head. A further analysis of this study (Reference 11) was done, and it was shown that 45 percent of these injuries occurred in the upper anterior quarter of the head, 42 percent in the lower anterior, 4 percent in the upper posterior, and 10 percent in the lower posterior, as shown in Figure 1. This illustration graphically portrays the preponderance of injuries occurring in the frontal area. The facial area also receives a very large percentage of the total head injuries, but the consequences of frontal and temporal injuries are much more severe because of the frequent brain involvement.

THE REQUIREMENTS OF A HEAD PROTECTIVE DEVICE

Early in the program of evaluating head protective equipment, the Engineering Division of the AeroMedical Lab at Wright-Patterson AFB, while testing and comparing the USAF P-1 and Protection, Inc.'s Toptex helmet, concluded that a helmet must have the following characteristics: "Non-penetration of helmet, minimum movement of the head, minimum peak acceleration, maximum energy absorption, minimum tendency to "bottom out" against the head, uniform protection over entire head, and minimum tendency for peak acceleration to become larger with increasing area of contact on the helmet." (Reference 7)

Figure 1. Illustration of Injury Site Frequency as Experienced in 800 Survivors of Light Airplane Accidents.

* Total of 101 percent due to rounding error.

In an article by J.S.P. Rawlins, the duties of the head protective helmet were summarized thus: (Reference 8)

1) Protection against penetration and abrasion,

2) Protection against deformation of the skull,

3) Reduction of rotational acceleration,

4) Reduction of average linear acceleration,

5) Reduction of peak linear acceleration,

6) Absorption of kinetic energy and

7) Distribution of impact.

He further states that to meet the requirements listed above, the helmet should have the following respective qualities:

1) It should be tough;

2) It should be rigid, not elastic;

3) Its surface should be free from projections to minimize torque;

4) Its surface should be smooth and have a low coefficient of friction to facilitate sliding over the opposed surface;

5) By uniform deformation, it should smooth out the acceleration curve;

6) It should convert kinetic energy to energy of compression or extension; and

7) It should spread the blow as widely as possible over the head.

Along with these criteria must be included consideration for unobstructed vision, free head movement, compactness, lightness of weight, thermal radiation, head contoured fit, positive retention, and a compatible communications system.

Again, to extract from J.S.P. Rawlins, the basic properties of a crash helmet, properly designed, are resistance to penetration, resistance to deformation, reduction of accelerations, and absorption of kinetic energy (Reference 8). The definition of proper design is entirely dependent upon the level of protection we desire to achieve. As stated by H.P. Roth, ". . . the most important purpose of a protective helmet . . . is not to make minor impacts comfortable, but to make major impacts survivable." (Reference 9) This statement not only implies the need for strict adherence to the principles of Rawlins, but also points to the need to eliminate carefully all of those factors which will reduce or jeopardize the effectiveness of his principles. This is to avoid, for example, the use of materials such as sponge-rubber pads solely for added comfort or the arbitrary selection of low levels of protection on the assumption that the human head cannot survive higher levels of energy input.

The preceding comments support the need for a strong, not easily yielding helmet; however, a word must be said about becoming too severe in the design requirements. First, if the designer of a helmet considers only energy absorption to be of greatest effectiveness, beginning right at the scalp level with no regard for comfort, utilization of the item will not be accepted in the field because of the unwearability over prolonged periods. The unyielding nature of good energy absorbing agents would make them hard and uncomfortable against the scalp. Secondly, and of extreme importance, the device must attenuate forces to survivable levels; it cannot be so strong and unyielding that it transmits forces without sufficient attenuation. Various laboratories evaluated the forces that the human head can endure, depending upon the rate of onset, duration, and magnitude of the force.

In order to define the maximum protection that a helmet should furnish, knowledge of the basic force phenomena encountered in high-speed impacts is required. From observations of free falls (References 1, 15), it was determined that survivors can sustain exposures of about 200 G to their whole heads (whole body) for durations of .105 - .03 second; pigs accelerated on sleds could sustain up to 125 G for durations between 0.04 and 0.08 second with reversible injuries (Reference 13).

In studying the forces to which survivors of race-car accidents are exposed, Dr. Snively has used a method of comparing the deflection of the liners worn by the survivors to test impacts on similar liners.

He states, "Six of the ten (survivors) showed liner deflections indicative of head accelerations well above 200 G, and three reached values of 450 G or more." Detectable neurologic residuals were not noted in any of the six cases (275 to 450 G) referred to (Reference 17). From these observations, it is reasonable to expect that a helmet should attenuate forces applied to the shell to within these ranges of acceleration. It is possible that these experiences could represent the extremes of biological variation in tolerance and do not necessarily mean that all individuals could survive these same force inputs.

More definitively, skull fracture might be considered the parameter on which the strength of the helmet should be designed, since less severe forces would result in reversible concussion and forces of only slightly greater magnitude would result in collapse or crushing of the skull. Gurdjian, et. al., has done very definitive work on this parameter by impacting cadaver heads and has found that ". . . the presence of hair, scalp, and intracranial contents had a negligible effect on the position of the resultant fractures, but not on the energy required to produce them. The energy ranged from 425 lbs. per square inch to over 900 lbs." (Reference 16) The accelerations experienced to produce these fractures varied from 240 G to 557 G with a duration of from .001 to .0019 second.

Therefore, the designer of helmets has much information available to determine what should be built into a helmet so as to provide maximal protection through proper selection of materials, ideal distribution of these materials, and best structural configuration of these materials.

Now that the problem of head injury and the need for protection have been discussed, the remainder of this presentation will deal with the Army's current helmet, observation of problems that have been encountered from an injury prevention viewpoint, and, finally, concepts on how these injuries could possibly be reduced.

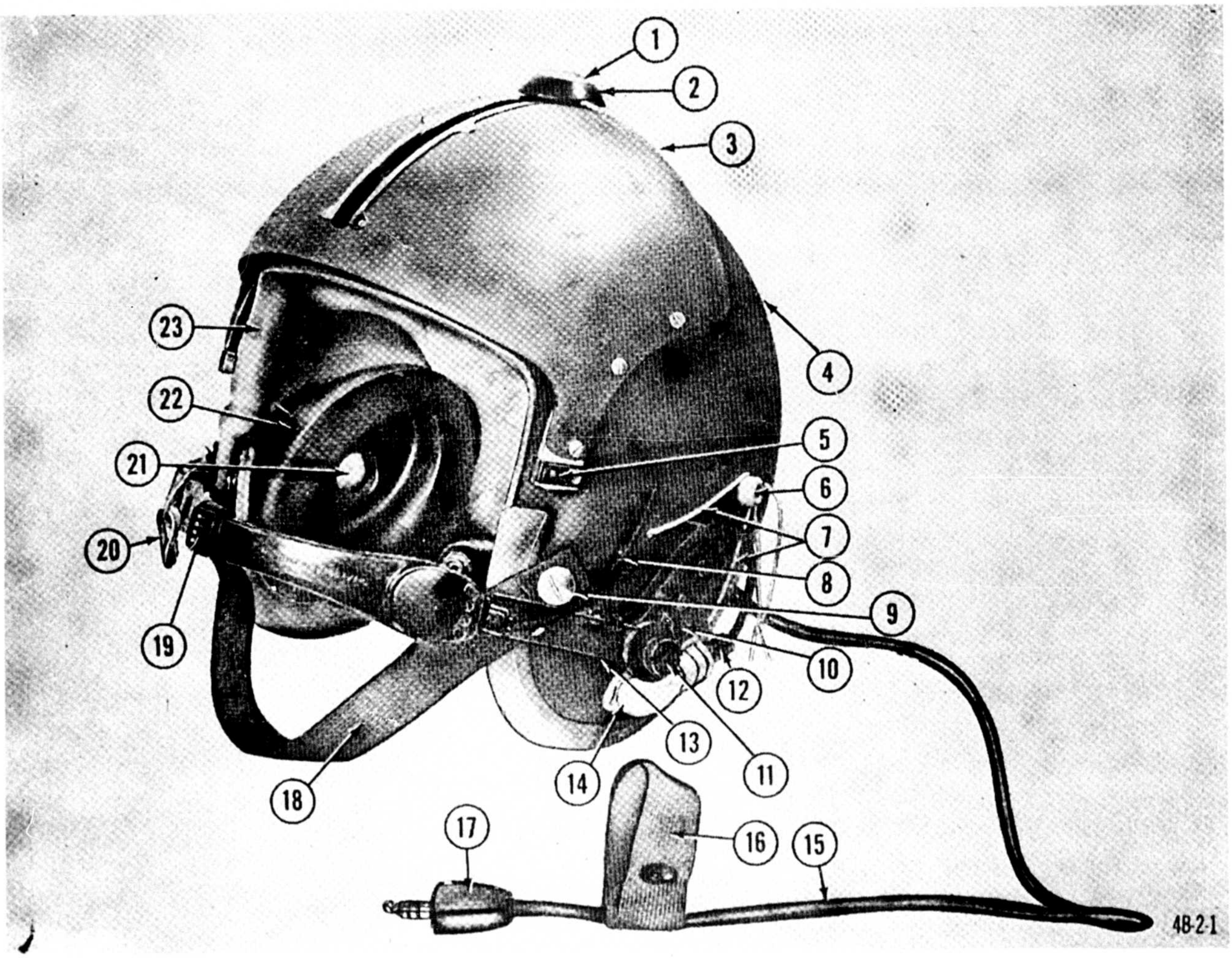
DESCRIPTION OF THE APH-5 CRASH HELMET

The APH-5 is manufactured in accordance with Navy specifications. The development of an improved protective helmet for air crews was initiated by the United States Navy through several independent research projects. Their final choice was the APH-5 helmet, weighing about 3-5/8 pounds. Molded from glass fabric and polyester resin, the outer shell of the APH-5 is approximately .070 inch thick; it provides force distribution and has penetration resistant qualities. A thin housing of the same material is rigidly attached to the front part of the helmet; it provides protection for a transparent plastic eye shield or sun visor when not in use. The edge of the shell is lined with a roll of dense foamed rubber in one piece. Provisions are made to install a microphone and earphones. A chin and nape strap are provided for retention purposes.

Attenuating liners are installed to dissipate impact energy. These liners, which are 9/16 inch thick, are molded from nonresilient cellular polystyrene and are cemented in three sections to the inside of the helmet to fit its contours.

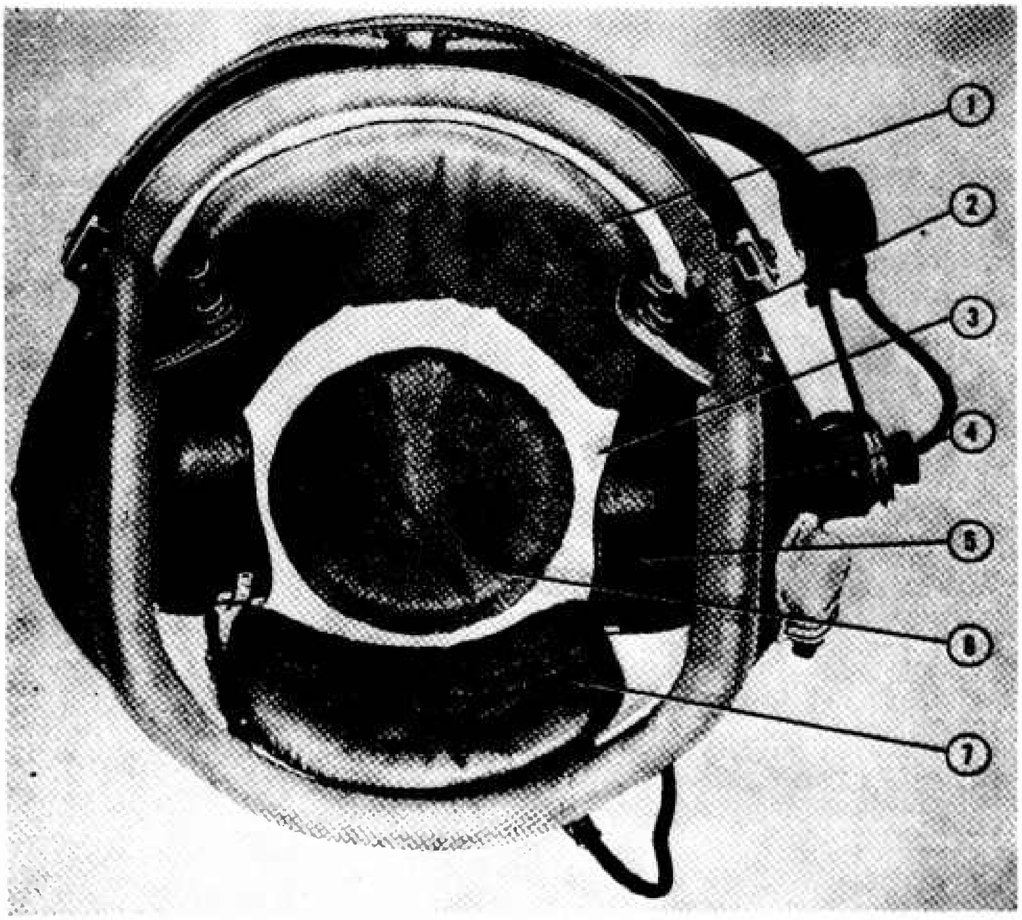
Front, top, and back sizing pads of a soft foamed plastic with a leather cover can be installed. They are of various thickness and have a twofold purpose: they permit fitting of the helmet to individual head contours by variation in thickness of the pads, and they provide comfort to the wearer by protecting the head from the hard liner in order to permit prolonged wear. A balance is thus obtained between stability and comfort.

Illustrations of the APH-5 crash helmet are given in Figures 2 and 3.



1. Button release
2. Button release housing
3. Eye shield housing
4. Helmet shell assembly
5. Keeper
6. Rubber bumper
7. Earphone adjusting cord
8. Microphone cord
9. Tee nut assembly
10. Bracket, microphone, MT-2015( )/PR
11. Microphone boom adjusting knob
12. Microphone plug, U-173/U
13. Microphone boom
14. Microphone jack, JJ-055
15. Microphone cord
16. Microphone cord attaching strap
17. Connector, plug, U-93A/U
18. Chin strap
19. Microphone, M-33A/AIC (with cover)
20. Chin strap release tab
21. Earphone, H-143/AIC
22. Earphone cushion, MX-2088/U (right)
23. Edge roll

Figure 2. Helmet, APH-5 Detail, External View.



1. Front sizing liner
2. Oxygen mask mounting tab
3. Shock-absorbent liner
4. Edge roll
5. Earphone cushion, MX-2088/U (left)
6. Crown sizing liner
7. Back sizing liner

Figure 3. Helmet, APH-5 Detail, External View.

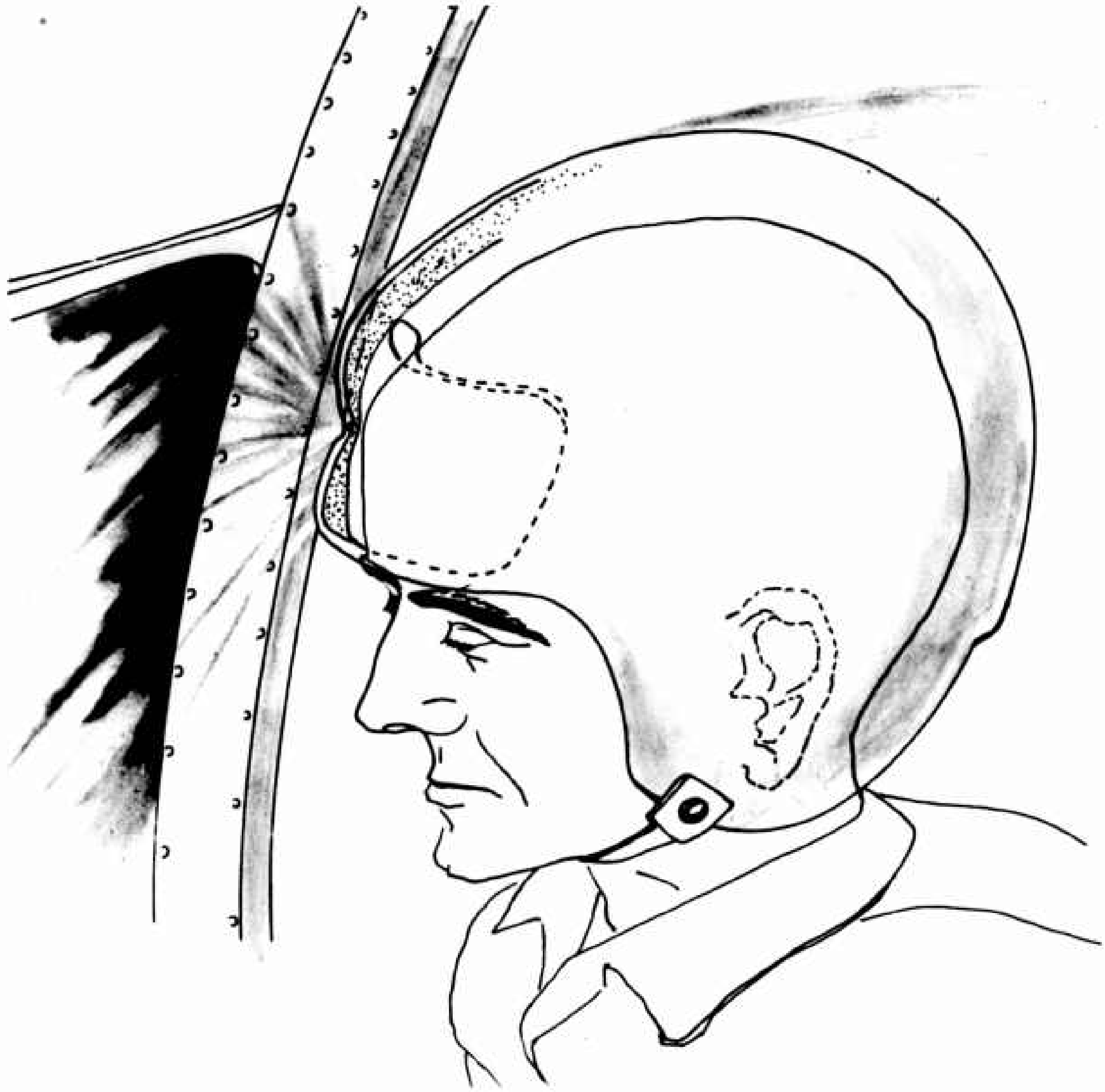


Figure 4. Illustration of Bottoming in a Helmet, Disclosing: A) Caving of Shell; B) Fracturing of Shell; C) Local Deformation of Liner; D) Magnification of Forces due to Bottoming of Sponge Sizing Pad.

APH-5 PROBLEM AREAS

THE SHELL

The shell of the standard APH-5 has shown in accident experience a propensity to various consistent types of failure: 1) tendency to bottom; 2) tendency to fracture on bottoming; 3) tendency to tear and fracture under shearing loads; and 4) limited resistance to penetration.

The tendency to bottom has been shown on occasions in field experience. Cases B, D, and E in the Appendix of this discussion illustrate this problem. What happens is that under a local impact, the immediate portion of the shell under the impact site caves, as illustrated in Figure 4. This caving reduces the area of distribution of forces through the shell and localizes the force in a small area of liner for dissipation. Thus, only a small amount of energy absorbing material is volumetrically reduced. If the maximum amount of deflection occurs, the shell bottoms and thus allows the force to be transmitted directly to the underlying skull. This localized application of force then can result in a very high focal load on the skull, resulting in fatal skull fracture and brain injury, even when the total G load to the whole head is relatively low and within survivable limits (see Case E, appendix). The spherical configuration of the shell allows ease of caving on the basis of weak geometric strength.

At first, it may seem that all caving is considered to be undesirable. This is not true, as caving actually expends force. The problem is only significant when the caving occurs too easily with only the immediate underlying liner being compressed while the surrounding areas of liner remain intact and uncompressed.

Often bottoming of the shell is associated with fracturing and tearing of the fiberglass shell material (Case D, Figure 15, appendix). In addition to the difficulties discussed in the previous paragraph, this tendency reduces the protective capability of the helmet by allowing invasion of the aircraft structure into the subshell sanctuary, where these foreign materials can inflict further damage by direct contact with the head.

Case D also illustrates the tendency of the fiberglass to tear when under shearing stresses (Figure 14, arrow 1). This occurrence, of course, implies very high loads and is brought about by the presence of snagging protusions on the external shell surface. The development of tears is undesirable, even though energy is absorbed in their production, as this leaves a vulnerable, exposed area for any subsequent impacts in the crash sequence.

The glass fabric shell has limited resistance to penetration by high velocity projectiles; because of this, the U.S. Army Quartermaster Corps has undertaken study of this problem. Inasmuch as the helmet is an integral component of the pilot's combat gear, this problem must be considered in the evaluation of the APH 5, even though it is not an integral concern for crash injury analysis. Because of the Quartermaster Corps' current research, further discussion of this problem will not be taken up in this paper

THE LINER

Styrofoam is the energy absorption liner material used in the standard APH-5. The practical capability of styrofoam to absorb energy in an impact situation, aside from its inherent physical qualities, is dependent upon distribution of the involved force through a maximum volume. The failure of styrofoam to absorb adequately the energy in many injurious and fatal situations has been due to focal or local loading when the shell fractures, caves, or bottoms. In these situations, the styrofoam dissipates energy maximally, but the volume of the material available for energy absorption is reduced.

The most striking feature with respect to the liner in the APH-5 has not been its failure, but rather its absence (Cases A, B, D, appendix). The absence of liner along the edge of the shell (and its replacement by a sponge-rubber roll) allows inward flexion of the shell, resulting in its direct contact with the skull under magnification by the sponge-rubber edge roll. This is an especially undesirable feature in the frontal area, as this is the most frequent site of impact to the head in aircraft accidents (Figure 5).

A second deficiency, by absence, is in the temporal area where the large earphones are located. No energy absorbing potential, save for the shell itself, is offered in this area; and transmission of force to the skull is unattenuated and even magnified by the sponge-rubber of the earphone. Further, the solid metal cone of the earphone permits concentration of energy in a small area over the temporal bone. Because of the large size of the earphone, energy absorption material has been cut away from the supra-auricular portion of the liner to allow commodious accommodation for these outsized pieces of apparatus (Figures 6 and 7).

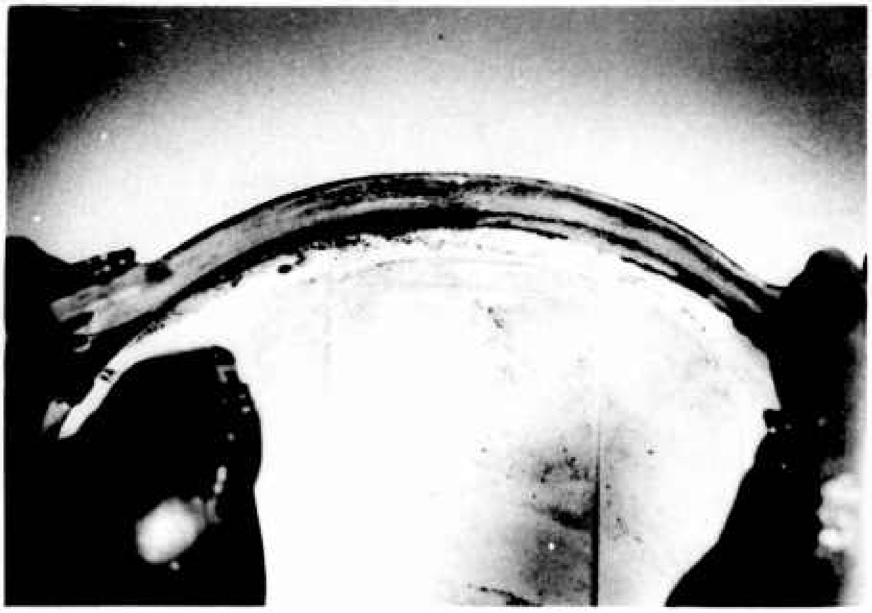


Figure 5. Photo of Frontal Edge of APH-5 With Edge Roll Removed. Note large edge of shell without underlying liner.

Figure 6. Photo of Temporal Area of APH-5 With Earphone Removed. Note cutting away of liner material in the supra-auricular area; absence in earphone area.

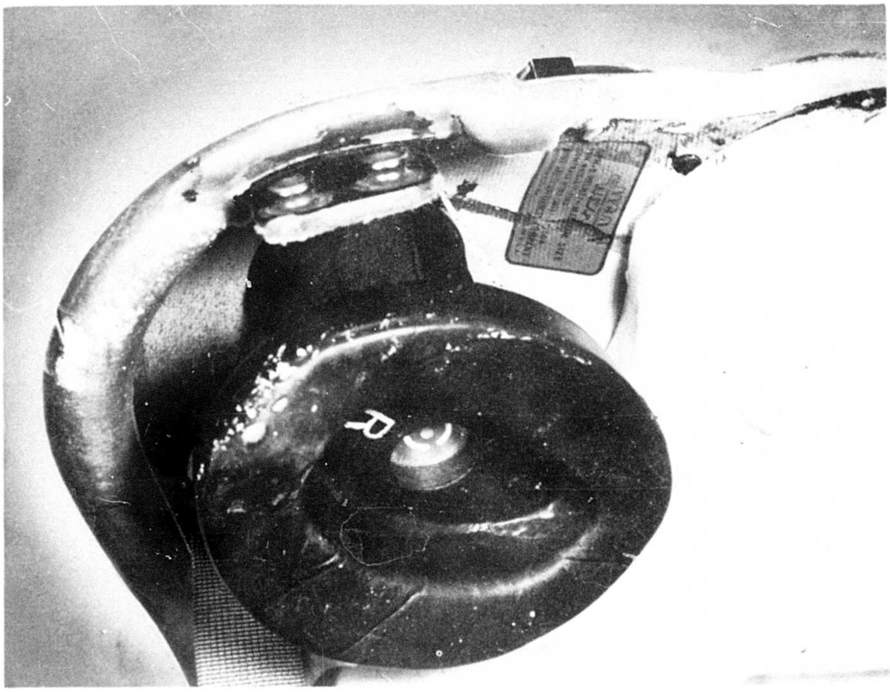


Figure 7. Photo of Large Earphone of APH-5.

No room is allowed for energy absorption in temporal portion of the helmet.

A third deficiency is inadequate thickness of the liner. When the volume of the energy absorption liner is deflected by 70 percent (Case D, E, appendix), the liner behaves as a solid and no longer is capable of energy dissipation. This deficiency is particularly significant in the frontal area, again, because most impacts occur in that area (Cases B, E, appendix).

THE EARPHONES

The main problems associated with the earphones are: 1) large size, displacing volume of available energy absorbing liner; 2) large center solid core; and 3) large sponge-rubber pad body. The displacement of the energy absorption liner and the presence of the solid earphone core have already been described in the previous discussion dealing with the energy absorption liner.

The large sponge-rubber pads reduce protection because of magnification of forces as well as volumetric reduction of the liner. Magnification of forces is the phenomenon in which the resultant force experienced is greater than the applied force because of lag. When the shell of the helmet is struck, the helmet is accelerated; however, the sponge-rubber pads merely compress without imparting an acceleration to the contained head. When the sponge-rubber is completely compressed, the head must suddenly accelerate at a much greater rate to attain the helmet velocity, as it has not participated in the acceleration up to this moment. Thus, the peak accelerations of the head, and particularly of the locally involved tissues, can be much greater than those of the helmet shell. This probably was an important factor in the fatality described in Case A, appendix.

THE PADS

The APH-5 helmet is fitted to the individual head contour by means of three foam plastic pads encased in leather. These pads are cemented to the liner and provide a comfortable fit over the hard liner material. These pads are a source of much annoyance in everyday use (Reference 3). They are a source of concern from a standpoint of safety as well, inasmuch as they are made of sponge material and will allow magnification of forces to occur as described in the preceding paragraph. This is augmented in many cases by the individual pilot's using a large-size helmet and filling in the gap between his head and the liner with the thickest sponge sizing pads available. This, unfortunately, allows for even greater magnification of forces.

THE RETENTION SYSTEM

Retention of the APH-5 helmet is achieved by a chin strap, which is attached to the exterior of the helmet shell, and a nape strap, which is attached to the interior of the shell. The nape strap spans the posterior of the helmet so as to anchor below the occipital prominence of the skull. This retention method does not seem to be satisfactory, as reports indicate that helmets continue to be lost in accidents. The loss of helmets usually is the result of: 1) failure of the retention strap material; 2) improper adjustment; or 3) rotation of the helmet over the head.

Case D in the appendix describes a case in which the chin strap failed at both ends. This weakness is repeatedly apparent at the sewn seams and at the anchorages to the helmet. The sewing and penetration hole at the attachment point weaken the strength of the strap, and a failure will invariably cause the helmet to separate from the head.

Separation is also frequently the result of improper adjustment of the two retention straps, the chin and nape straps. The chin strap is frequently worn in a loose fashion because of the discomfort associated with snubbing it up properly. Improper adjustment of a nape strap is usually a matter of neglect in initial fitting of the helmet. The pilot frequently fails to anchor the strap in its proper adjustment hole, and emphasis on the need for proper adjustment of this strap is often overlooked by safety officers and flight surgeons in the field.

A very important reason why helmets are lost is that the posterior anchorage is limited to the occipital protuberance. This area is relatively small, and any rotation of the helmet with respect to the head will displace the nape strap out from under the protuberance (Reference 3).

Case C, appendix, describes still another difficulty of the chin strap, in which the strap produced a laceration. This is augmented by the tendency of the strap to roll into a cord under loading, thus reducing the area of contact against the skin.

STRESS CONCENTRATION POINTS AND PROTRUDING OBJECTS

Screws, knobs, and specialized metal objects are in profusion on the external surface of the APH-5, totaling over 30 in number. These include the visor adjustment knob, the visor shield, the visor keeper (with 4 external and 3 internal screws), 3 screws for the chin strap-oxygen mask anchorage on each side, 2 screws for earphone attachment (each side), connection mount for microphone avionics (left side only), 1 screw for earphone retraction string (each side), and 1 screw for nape strap attachment (each side). The avionics connection cable attachment in the back is not hazardous, as this portion of the helmet is essentially free of impacts.

These articles are all important as injury producers for three reasons: 1) they allow contact with the environment to be concentrated on one small point; 2) they are associated with holes in the shell which weaken its integrity; and 3) they snag on objects.

With the load of an impact being applied focally on one small area of the shell, combined with the weakening feature of a hole, the result is often fracture of the shell, with invasion of the impacting agent into the helmet to inflict injury to the head. Point concentration increases the tendency of the shell to bottom, and the already present hole initiates a fracture or tear. This is illustrated by Cases A and D in the appendix.

The protrusion of these articles from the surface of the shell allows points of snagging when impacting objects strike the helmet in an oblique or tangential fashion. This may result in fracturing or tearing of the helmet, but more important, it imparts severe angular accelerations to the helmet and head which may cause central nervous system injury by the severe rotational jostling of the brain, or may cause neck fractures and cervical cord injury (Case D, appendix).

THE VISOR

The APH-5 visor is made of an acrylic plastic, fitted to the front of the helmet in a keeper shield. The acrylic plastic shatters easily and produces razor-sharp edges under impact (Figure 8). This has been described in Reference 3.

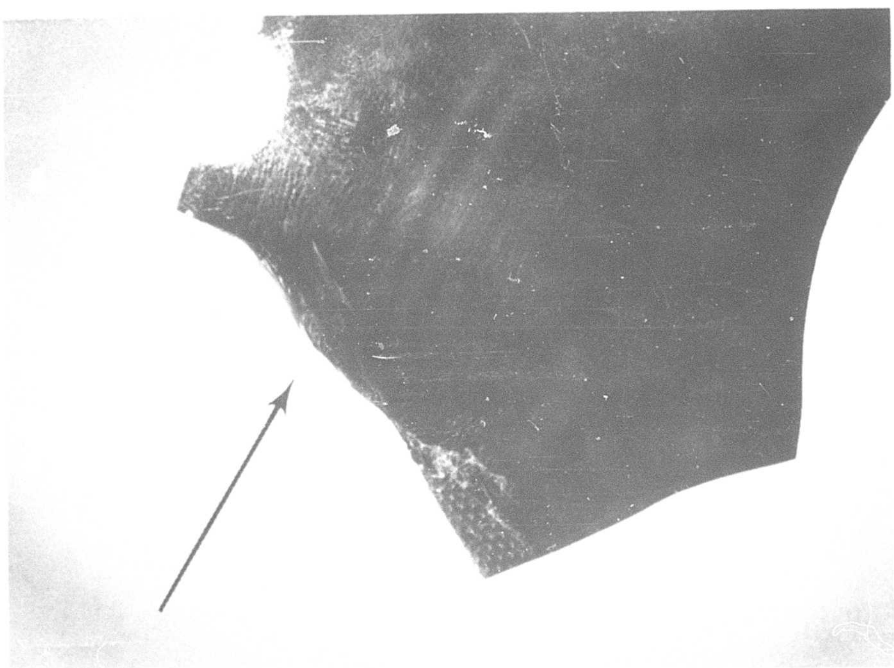


Figure 8. Photo Showing Razor-Sharp Margin of Fractured Acrylic Plastic Visor From APH-5 Helmet.

As a result of this fracture characteristic, the sharp edges have been known to produce facial lacerations (illustration, Figure 9) and are a potential hazard to the eyes.

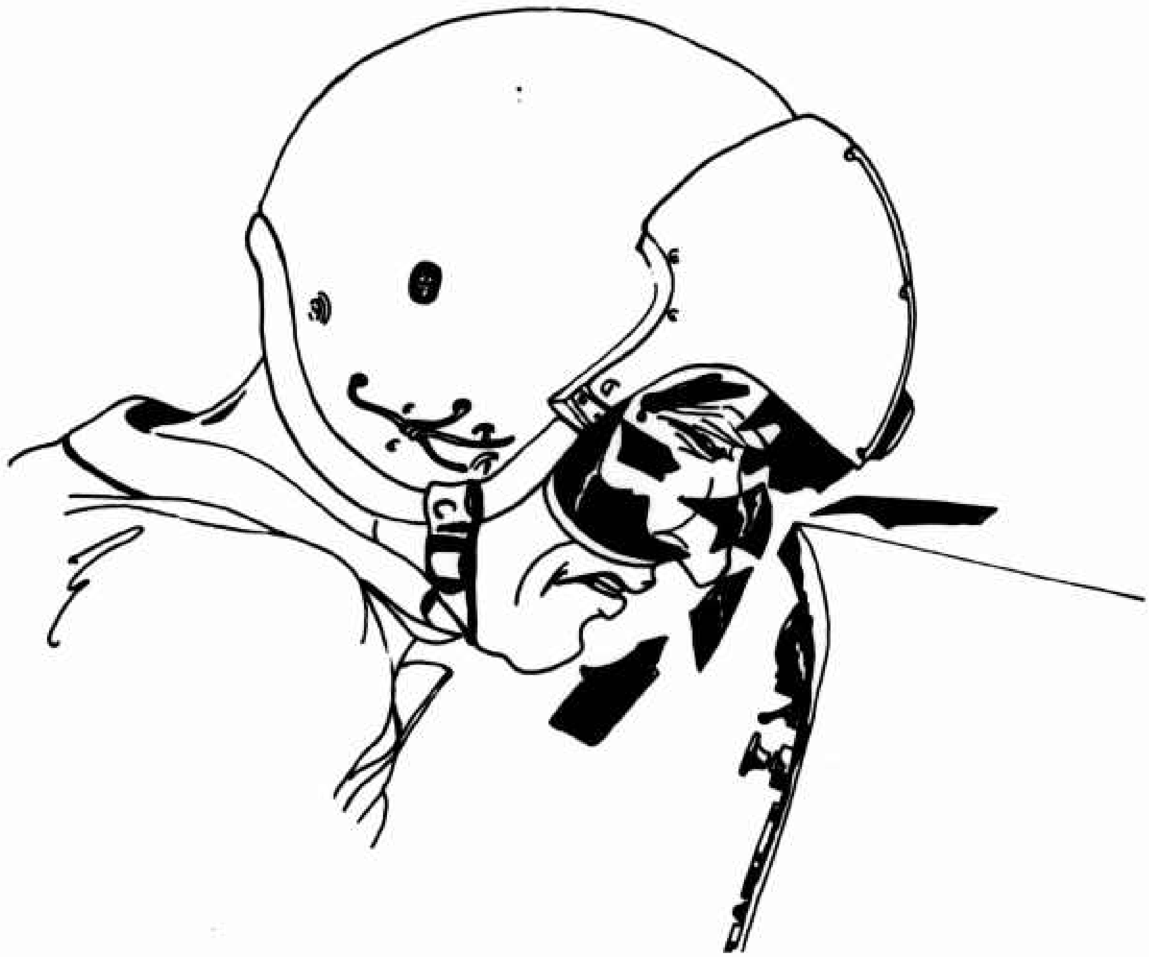


Figure 9. Illustration of a Case of Laceration of the Skin Due to Shattered Visor (Reference 3).

The major problem with the visor in Army accident experience from an injury standpoint, however, is that the prominent keepers are points of snagging and stress concentration (described under the previous heading dealing with stress concentration points and protruding objects).

THE MICROPHONE

The microphone of the APH-5 helmet is mounted on a boom which is attached to the left side of the helmet shell with an adjusting knob. In addition to the microphone's providing a snagging point, the bulkiness of the installation adds weight to the helmet.

WEIGHT

The APH-5 helmet weighs a little over 3-1/2 pounds without oxygen mask. This is not considered excessive, but the distribution of this weight is an important factor. Many aviators complain about the weight of the APH-5, but it is suspected that this is caused by the top-heavy feeling when the helmet is worn. It seems that the center of gravity of the helmet is located above the center of gravity of the human head, which causes the neck muscles to tire faster and thus imparts a feeling of heaviness of the head and helmet. Proper distribution of the helmet weight around the head is therefore important.

COMFORT

The APH-5 is uncomfortable for many reasons, the coverage of which is best accomplished by reviewing the USABAAR Army Aviation Helmet Experience Report (Reference 3) The reason for inclusion of a comment in this report is that comfort is a very important consideration in assuring proper wearing of the helmet at the moment that it is needed.

The features of the APH-5 that produce discomfort are summarized as follows: 1) large area sizing pads which prevent dissipation of heat through evaporation of perspiration and cause tight feeling from massive uninterrupted contact with scalp; 2) high center of gravity, causing helmet to feel top-heavy and resulting in increased neck-muscle load; 3) inadequate ventilation (due to large sizing pads); 4) nonconformity of liner contour to skull contour because the liner is spherical while the skull is a complex of parabaloidal segments (this causes local portions of the skull to bear more pressure than other portions because of the asymmetry of the two curvatures, and these pressure areas become increasingly irritating when they have to be endured for prolonged periods of time); and 5) large earphones sometimes become "sealed" to the side of the head by perspiration, causing annoying pressure differential on descent.

Thus, a number of the deficiencies of the APH-5 are summarized below:

1) The shell has a tendency to bottom easily, to fracture, and to tear, and has limited resistance to penetration.

2) The spherical configuration of the shell does not provide maximal geometric strength.

3) The shell has many protuberances which are points of concentration, snagging, and initiation of fractures.

4) The energy absorption liner is not utilized sufficiently in areas where it is maximally needed, i.e., temporal and frontal areas.

5) The energy absorption liner material is of insufficient thickness in the frontal area.

6) The earphones are bulky, displacing energy absorption material from the temporal area.

7) The earphones are of sponge-rubber, allowing magnification of forces in the temporal area.

8) The earphones have a solid core, allowing unattenuated transmission of energy to the temporal skull.

9) The sizing pads are of thick foam plastic, allowing magnification of forces.

10) The energy absorption liner is of spherical contour, requiring thick sizing pads to accommodate the irregular skull contour.

11) The retention system is weakened by seams and screw attachments.

12) The retention system has insufficient contact area with the base of the skull.

13) The retention system straps have a tendency to roll into cords, further reducing contact area and becoming cutting edges.

14) The nape strap has a tendency to lose anchorage under the occiput by rotation of the helmet.

15) The acrylic plastic visor fractures form sharp edges and cause lacerations.

16) The visor keeper and shield is bulky and heavy.

17) The visor keeper is a prominent protrusion, causing failure of the shell by snagging and concentration of forces.

18) The center of gravity of the APH-5 is too high in relation to the head's center of gravity, causing top-heavy imbalance and neck muscle fatigue.

19) The APH-5 is uncomfortable because of the lack of ventilation and heat dissipation due to bulky sizing pads.

20) The APH-5 retention system is frequently felt to be uncomfortable, causing improper adjustment by the wearer.

Truly, the APH-5 has saved lives and reduced injury; however, the above list of problems certainly indicates that there is room for considerable improvement.

Therefore, the following discussion will deal with concepts and recommendations that could reduce or eliminate these problems.

CONCEPT OF RESOLUTION

Using the APH-5 as a basis for study in the development of concepts for recommendations by which its deficiencies can be utilized in organizing thought for design of an ultimate head protective device (hereafter referred to as HPD), it is of paramount importance that one retain the fact in mind that the device is to be worn for one purpose — head protection.

Special consideration in engineering organization must be applied to design the structure according to the specific environment in which the helmet is to be used; for purposes in this discussion, all environmental considerations are given to employment in Army aircraft.

Following are conclusions drawn from the analysis of the APH-5; concommitantly, concepts are included for resolution in a desirable HPD.

THE SHELL

The APH-5 shell has not demonstrated desirable strength, though it is not wholly inadequate.

The shell of an HPD must have sufficient rigidity to allow distribution of energy to the underlying liner over as large an area as possible. This rigidity must not allow caving, bottoming, or premature fracturing, as any of these occurrences will, in effect, reduce or destroy the function of the shell.

Dynamic rigidity can be achieved not only by selection of the most capable material but also by the choice of geometric configuration which can greatly improve the strength and force distribution. The configuration of the APH-5 is a sphere; however, geometrically, a paraboloidal sector provides much greater structural strength than a spherical sector using the same material (illustration, Figure 10 D, E). Certainly this is not an unknown fact to nature (egg shells and cranial vaults are shaped as compound paraboloids rather than as spheres). This structural design has the advantage of significantly increasing the structural strength without increasing the weight.

Coupling this concept with the known injury frequency distribution as discussed earlier, it is apparent that the portions of the helmet that receive the most blows should be structured the strongest. Without going any further than looking at a human skull, the frontal area would be noted to be geometrically the strongest, as this represents the vertex of a paraboloid sector. As a result of exposure and selection, this portion of the skull, through evolution, has come to be paraboloid. And so, with this same area of the head, the frontal area, receiving the most blows in aircraft accidents (Reference 1, 11), it is desirous to provide the greatest protection in this area. The same study reveals that the occiput and vertex of the head receive the fewest significant blows; therefore, these areas need the least protection. Figure 10 portrays how this concept of geometric strength could be applied to a helmet design so as to provide greatest strength in the areas where it is most needed. The formulation of ideal paraboloidal sectors is presently being studied and will be presented in the near future.

Holes should be avoided in the frontal and lateral areas of the shell, as these weaken its structural integrity. Round holes may be considered acceptable in the posterior portion of the shell if they are small in diameter and not closely spaced.

STRESS CONCENTRATION; PROTRUDING OBJECTS

The APH-5 shell is weakened and its protective capacity is reduced by the presence of protruding objects and stress concentration points.

The shell must have a clean and smooth surface with as low a coefficient of friction as possible. There must be no protruding screws, bolts, attachment points, guides, knobs, visors, guards, keepers, or other objects which would allow focal concentration of force to the shell, or snagging of the helmet.

All of the components of the helmet must be so integrated into the unit structure as to allow the surface to be absolutely clean. If any protrusions are to be present, these must be in the posterior portion of the helmet, as this area has a very low accident contact exposure.

Reasons for avoiding protrusions and stress concentration points are based on the discussion in the APH-5 deficiency section of this paper; it therefore suffices to say here that these must be avoided in a desirable form of HPD so as to prevent such conditions from occurring. Figure 10 represents the concept required in an ideal helmet surface clean of any force concentration or snagging points.

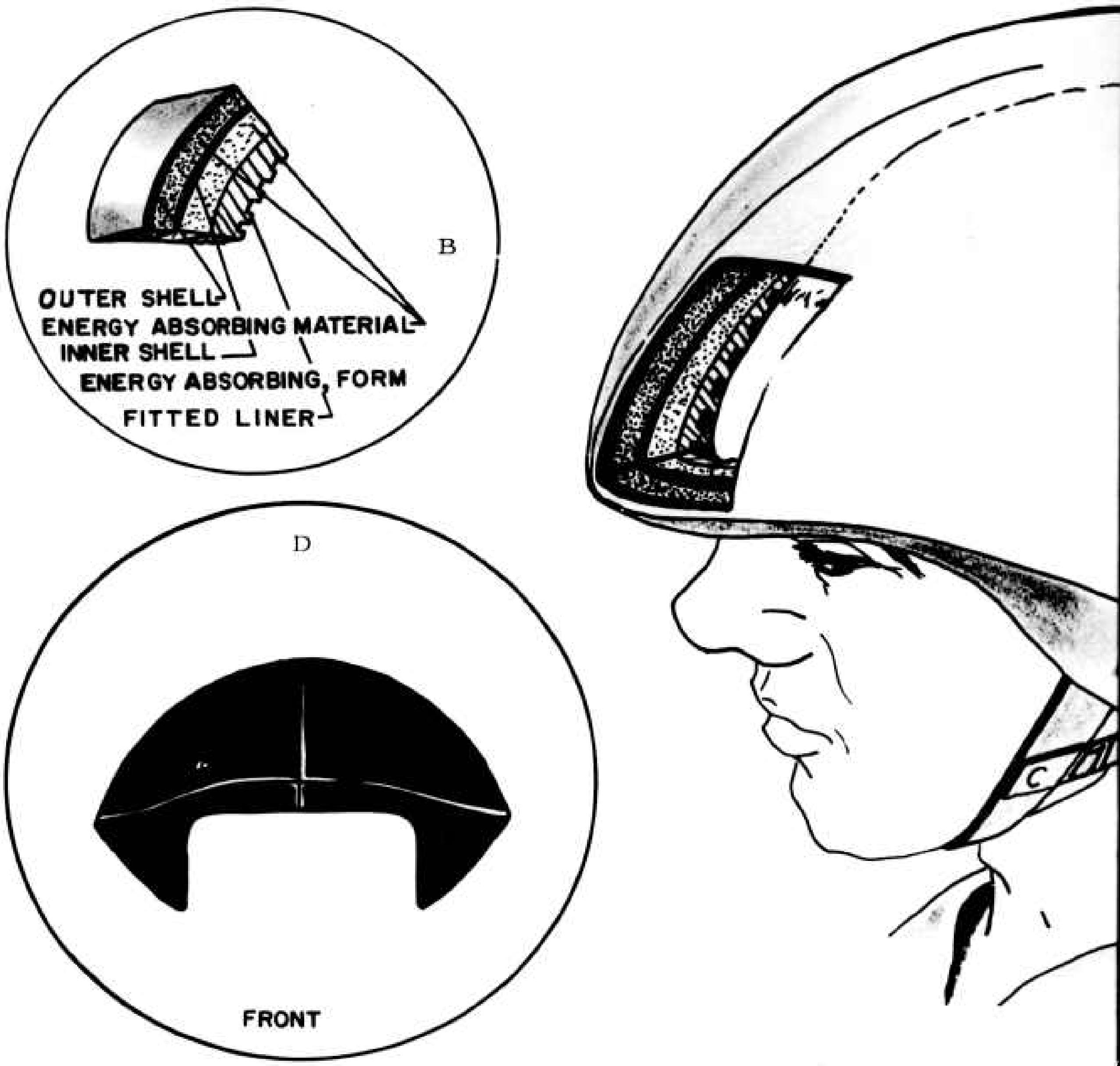
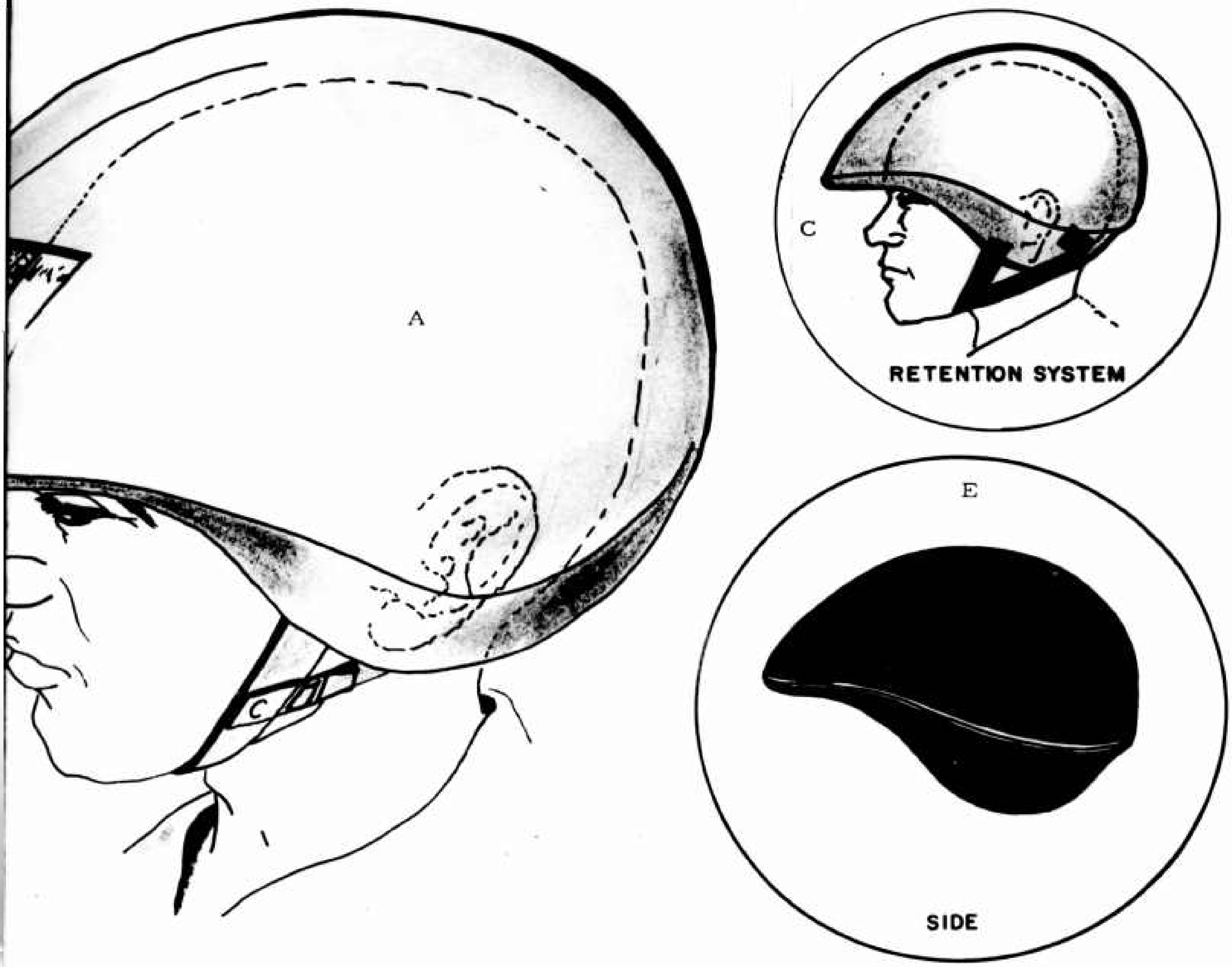


Figure 10. Illustration of Concepts of Resolution of Som

A. Overall View of Helmet Concept With Completely Clean Surface, Free of Any Protrusions.

B. Cross-section of Shell and Liner, Showing One Concept Which Employs a Second Shell for Greater Distribution and Energy Absorption. Note the "waffling" of the form-fitted inner liner, which allows greater circulation of air and decreases the local area of pressure contact.



epts of Resolution of Some Prominent Problems Encountered in the APH-5.

pletely Clean Surface,

One Concept Which
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C. Concept of a Restraint System Which Allows Circumferential Anchorage of the Helmet.

D. and E. Frontal and Lateral Views Depciting Concept of Paraboloidal Segments in the Areas of Greatest Injury Frequency.

2

THE VISOR

On the basis of crash protection, it would be best not to have a visor because of its interference with the basic protective features of the helmet.* Should a visor be necessary, it must be included in the design of the helmet so that it is integrated in such a manner that it does not impair the overall protective requirements of the HPD. Its component parts must not protrude from the external surface, where they become sources of snagging or force concentration. Its weight and the weight of the component parts must be minimized so as to keep the total weight of the helmet low. The material used in the visor must be nonshatterable; or if it does shatter on impact, it must not shatter in such a manner as to form sharp edges.

THE LINER

The APH-5 liner is of insufficient thickness to absorb energy of the magnitude frequently experienced in Army aircraft accidents.

The liner of any HPD must be of sufficient thickness to provide adequate absorption of energy so as to attenuate externally applied forces to survivable limits (internal). Many excellent energy absorbing materials are presently available; consequently, the criteria for selection can be satisfied easily.

These criteria are that the material must be nonelastic; of relatively low density, capable of absorbing large amounts of energy by deformation; capable of large volumetric destruction before becoming elastic or solid in behavior. The presently used styrofoam is a satisfactory material as long as the deflection required in an impact is not greater than 70 percent; after this much deformation occurs, the styrofoam becomes solid in behavior.

Figure 1 discloses injury frequency sites, and awareness of this fact introduces another concept of how best to design an HPD. Since the

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* The reason for the present visor configuration on the APH-5 is to provide windblast protection and to improve retention during high-speed ejection. The need for crash protection greatly outweighs these two factors in the Army's mission. Retention could be assured by a proper retention system while the danger to life by windblast is much less significant than the dangers of impact injury to an inadequately protected head.

fronto-temporal preponderance is obvious, as was brought out above in the shell discussion and in the illustration, not only does geometric design of the shell allow greater effective strength of the shell to be obtained, but the volume of liner in these areas of high impact density can be increased also because the volume of a paraboloidal sector is greater than that of a spherical sector. Thus, since the amount of energy absorbed is a factor of the volume of energy absorbing material deflected, greater protection is offered and the stopping distance is increased. Also, it is apparent that this allows thinning of the liner material in the areas of low injury frequency, thus allowing conservation of weight or at least getting maximum utilization of most of the weight of material that must necessarily be carried, as the displacement of energy absorption material from the low-frequency injury sites to the high-frequency injury sites does not increase the overall weight but greatly increases the protective efficiency of the helmet.

Therefore, the concept of paraboloid sector configuration not only increases the geometric material strength of the liner, but also positions the energy absorbing liner material to where it is most critically needed in aircraft accidents. (This may not be true for football players or race car drivers, with whom roll-over and ejection become a problem; as their contact site frequency may be very different.)

THE INNER LINER

Maximum utilization of energy absorbing capability of the liner implies that there should be no magnification of forces between the head and the liner. This is not achieved by strap suspensions or foam pads. The materials that are good absorbers at high energy levels have minimal elasticity; however, these materials cannot be applied directly to the scalp, as the pressure of simply the weight of the helmet would be too uncomfortable. Therefore, a pliable material must be introduced between the high energy absorbing liner and the head. A material with the energy absorbing characteristics of Ensolite would be very favorable, but, unfortunately, Ensolite itself will develop permanent deflection under prolonged pressure and is consequently unsatisfactory. Pressure set that does not progress to complete collapse of the material could be a very useful feature, as it would provide individual fit to be achieved simply by wearing the helmet. In time, the gradual settling of the liner would provide a fit according to the contours of the wearer's head. The problems of comfort and ventilation are taken up separately; however, they cannot be considered without full cognizance of their relation to the overall protective requirements of the liner.

RETENTION

The retention system of any HPD must be positive and secure even to the most severe limits of human tolerance to deceleration. It must retain the helmet not only in linear deceleration but in angular deceleration as well. Further, it must be simple to use, allowing application and removal of the helmet easily. Therefore, the motions involved should be two — fastening and adjusting — preferably both done from the same point.

The accompanying illustration shows a concept of such a device whereby the helmet is secured by circumferential anchorage to the base of the head, applying retention to the chin and occipital-nuchal protuberances primarily, but facilitating these by tying them together, not allowing them to spread and slip over the prominences to which they apply (Figure 10, illustration C).

The device would be snap-locked in donning the HPD, preferably on the right or the left, according to the handedness of the wearer, and then adjusted to a snug fit by tightening the chin strap portion. Doffing would be simply the reverse procedure.

Alternate methods could be conceived, but, considering that rotary-wing pilots are subjected to severe angular accelerations in accidents, it is very important that the nuchal retention remain secure throughout the range of survivable rotary excursions of the head and body. There are arguments that at times it would be better if the helmet would come off, particularly if snagged, so as to prevent torsion of the head on the neck; but if the external contour of the helmet is clean, snagging will be virtually eliminated, thus reducing the probability of this problem. Also, it is certainly of no value in protection on secondary or tertiary impacts if lost at the initial impact. Therefore, retention must always be considered to be of paramount importance in all situations.

AVIONICS

The APH 5 avionics system is too bulky and space-consuming, in that it displaces energy absorbing material from the temporal portions of the helmet.

The earphone and microphone systems must be so designed and arranged that they do not impair the protective function of the HPD. The means of providing auditory perception is most critical, as it must not hinder the HPD's ability to absorb energy and afford protection laterally. The use of large earphones is not satisfactory, as too large an area is occupied in the lateral compartment of the helmet which should be occupied instead by energy absorbing material. The pads of earphones are often of sponge-rubber, which allows magnification of forces; further, the earphones have hard, metal internal parts, which allow concentration of forces focally and direct transmission of unattenuated force. Therefore, the auditory compartment must be miniaturized, perferably located within the external auditory canal, and should not replace the lateral energy absorbing liner.

The microphone system should not be located on the end of the boom, as this requires attachment points on the helmet shell as well as being a possible source of injury by piercing or by breaking and forming sharp edges.

Figure 11 demonstrates a concept of avionics that is separate from the shell and, as such, does not interfere with the primary function of the HPD. The earpiece is a common hearing-aid variety, and the microphone is a simple throat microphone. An ancillary advantage to such a system would be that the avionics could be kept intact for emergency use while allowing discarding of the HPD.

COMFORT: FIT, WEIGHT, AND VENTILATION

These factors are all conditions which affect the wearability of any HPD. It is very easy to conceive of a "device" that will provide protection at the time when it is needed, but it is quite another matter to satisfy the subjective requirements that will assure its being properly in place when it is needed.

Proper fit is not only important from a standpoint of comfort but also from the standpoint of providing a continuum of energy absorption from the skin to the shell without unnecessary intervening dead space or elastic filler material that will allow magnification of forces. Further, because the head is not spherical in contour, while the energy absorbing material contour of the APH-5 is, pressure points of increased stress occur between the asymmetrical curves of the head and liner.

Therefore, fit should be on an individual basis, particularly with respect to the inner liner material. The shell and outer liner material

Figure 11. Avionics Concept Illustrating Earpiece and Throat Microphone Which Are Completely Separate From the Helmet. This arrangement has the advantage of not interfering with the energy absorption capability of the helmet, and also can easily be retained for use with rescue radio gear, etc.

can be standardized to uniform configuration; for best fit, however, the inner liner should be a molded relief of the particular peculiar anthropometric architecture of the individual wearer's head in order to provide comfort as well as protection. To compromise this is to compromise an estimated investment of $100,000 - $200,000 and a career of 20 or more years in an Army pilot's head.

Weight has several facets of concern: 1) the HPD must be light for comfort's sake as the musculature of the neck can bear only a limited amount of weight; 2) it must be light for ease of maneuverability of the head; and 3) it must be light to minimize its added loading on the vertebral column during vertical deceleration.

Therefore, the materials selected must total a minimum weight without jeopardizing protection. This can be accomplished by miniaturized avionics, redistribution of energy absorbing materials for greater protection rather than "blind" increase generally, and avoidance of superfluous use of ancillary items such as the heavy visor guard.

The weight of the helmet must be balanced in relation to the head, with the center of gravity of the helmet as low as possible to prevent a feeling of top-heaviness. This can, in part, be achieved by displacing the unused vertically located energy absorption material into the frontal and lateral areas of the helmet and by eliminating the heavy visor shield.

Closeness of fit and low heat transfer through the liner produce a stagnant environment and prevent dissipation of heat through evaporation of sweat and moisture or by conduction and radiation. Thus, ventilation and heat transfer become important aspects of any concept.

A feature that could be incorporated would be the use of ventilation holes. Since the posterior portion of the head receives very few blows, one could safely perforate this area with small ventilation holes without significantly jeopardizing the protective requirements because of the infrequency of injury in this area. Thus, convection movement of air would be provided in a limited degree.

Forced air could be used if it would be necessary; however, this would require a blower to force the air and appropriate connective devices. The connection to the HPD would, of necessity, be in the posterior portion, and ducting could be provided in the energy absorption liner for distribution.

A very promising concept for cooling of the liner would be the use of thermoelectric heat transfer devices, which can be made very small and imbedded in the surface of the liner (Reference 18) With these, the temperature of the liner could easily be regulated by the pilot's controlling the flow of electricity through the transfer cells (Reference 19)

INCLUSION IN OVERALL ENVIRONMENT

Finally, the use of any protective device must again be considered in its operational environment. To begin to conceive of an apparatus that will provide maximum protection to a pilot's head in the event of an accident requires that simultaneous consideration be given to all of those other injurious features of aircraft, since the most protective of head protective devices will fail in an overwhelmingly lethal environment. This means that crashworthiness, occupant restraint, environment delethalization, aircraft energy absorption structures, and escape and rescue provisions must be provided as maximally as practical within the Army's mission.

The type and performance capability of the aircraft that are to be used must be considered in the design of the helmet. Are ejection seats to be used? Will the pilot have to go down with his craft? Is the mission at such low levels that bail-out or selection of suitable landing site is not possible? The predominant operational environment becomes important in many aspects of design selection. For example, as has been pointed out earlier, the visor, as it presently is designed, is a useful item to the pilots who eject (and by ejecting, remove themselves from the ensuing aircraft crash environment). On the other hand, this same visor becomes a hazard that greatly reduces the protective capability of the helmet for the individual who is obligated to crash or is not able to make a timely exit from this aircraft. (For purposes of glare protection, the pilot who crashes would do best with only nonshatterable goggles or lenses, and these same items could provide atomic-blast flash blindness protection as well. These means of eye protection from light would not reduce the efficacy of the helmet.)

CONTINUAL OBSERVATION

Beginning with the present APH-5 and continuing on with any future head protective device, close observation and analysis of all accidents involving impacts to the helmet and/or head should be performed. Just as every drug used to cure or prevent disease must be kept under close scrutiny, so should this preventative medicine device called "the helmet".

It should be studied to determine the forces applied to the shell, forces transmitted to the head, damage to the helmet, injury to the head, role of ancillary items on the helmet in producing injury, role of environment in producing injury to helmet and head, efficacy of helmet in preventing or reducing injury, etc. Without such information, there is no way to make sound judgments for conceiving improvements or supporting good concepts.

Therefore, it is proposed that all Army helmets that have been involved in aircraft accidents in which an impact occurred to the helmet be studied. This would cause no undue financial burden as far as replacement is concerned inasmuch as, once the helmet has been involved in an impact and deflection has occurred within the liner, it is unsuitable for further use, as its protective potential has been reduced. Consequently, a new helmet would have to be issued anyway.

Experience with the APH-5 has provided the basis for making several recommendations and has stimulated a number of concepts. Most of these are not new, but reiteration is apparently in order.

1) The shell should be rigid enough to prevent caving and bottoming.

2) The shell should not tear.

3) The external surface should be free of protrusions.

4) The external surface should have a low coefficient of friction.

5) The shell should be designed in a strong geometric configuration according to known impact site frequencies.

6) The liner materials must uniformly deform to smooth out the deceleration curve.

7) The outer liner should be thickened in the frontal and temporal areas.

8) The shell and outer liner should be contoured according to anthropometric averages.

9) There should be no dead air space or elastic material between the scalp and shell.

10) There should be no solid metal structures between the head and the shell.

11) The inner liner should have energy absorbing qualities and should not be highly elastic.

12) Retention must be positive, utilizing circumferential anchorage to the base of the skull.

13) Specialized ancillary equipment (avionics, visors, etc.) must not reduce protective capability.

14) Specialized ancillary equipment (avionics, visors, etc.) must not produce injury within themselves.

15) The overall weight must be kept as minimal as possible.

16) The center of gravity must be as low as possible.

17) Comfort must be provided by whatever means that will not reduce the protective qualities of the helmet.

18) Design of environment should be delethalized.

19) The mission must be considered in the design.

20) Continued observation of crash experiences and laboratory analyses must be made.

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APPENDIX

ACCIDENT ANALYSES

CASE A

Description of the Accident

The aircraft was ferrying combat troops in mountainous and heavily wooded terrain, when the pilot experienced difficulty in maintaining air speed and altitude. A turn was initiated but could not be completed due to a narrow ravine, and the aircraft was committed to a forced landing. The aircraft lost its rear rotor due to contact with trees and rolled to the left, impacting on its left side at the pilot compartment. After initial impact, the rear section of the aircraft settled, with the tail cone wedged between several trees. The copilot suffered a fatal head injury.

Helmet Damage

At impact, both cockpit seats failed and permitted the occupants in the seats to be thrown violently to the left. The copilot, who was seated nearest the point of impact, struck the left cockpit support member with the left side of his APH-5 helmet, at the keeper of the eye-shield housing. The impact marks on the helmet are indicated in Figures 12 and 13 (arrows). The shield housing broke due to the concentration of force in a small area. This permitted the outer shell to bend inward, resulting in a fracture of the shell approximately one inch in length at the point indicated by arrow 2, Figure 12. This fracture of the shell occurred just along the margin of the energy absorbing liner.

Injury Analysis

The energy transmitted through the helmet produced a fatal lesion by causing an intracerebral hemorrhage with development of a hematoma in the right fronto-temporal area. All medical information is not available, but since the blow occurred to the left temporal area, the right-sided hemorrhage occurred either as a result of contrecoup or as a result of severe agitation of the brain when the head was suddenly angularly accelerated.

The helmet offered little protection because the shell fractured and

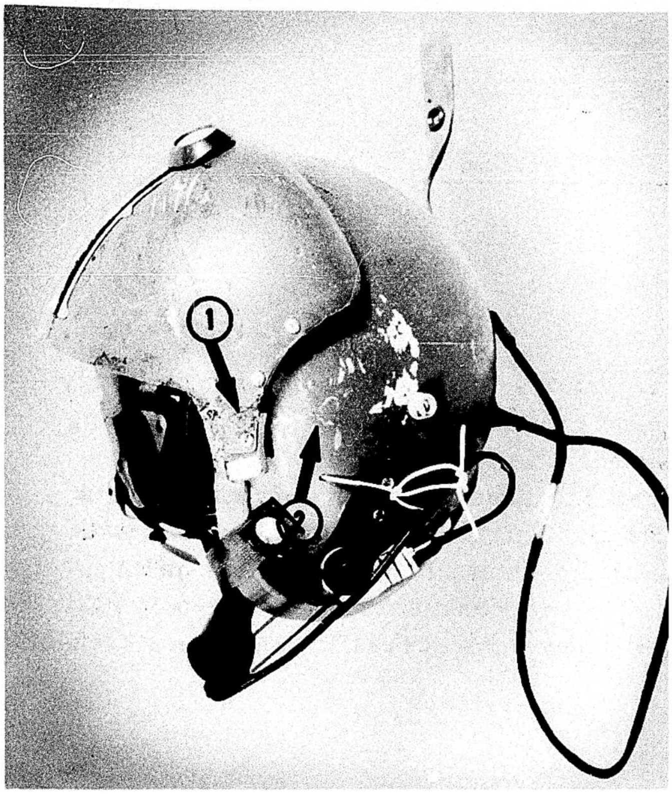

Figure 12. Impact Area of the APH-5 Helmet.
Arrow 1 denotes the point of impact on the visor housing.
Arrow 2 shows the fracture of the outer shell.

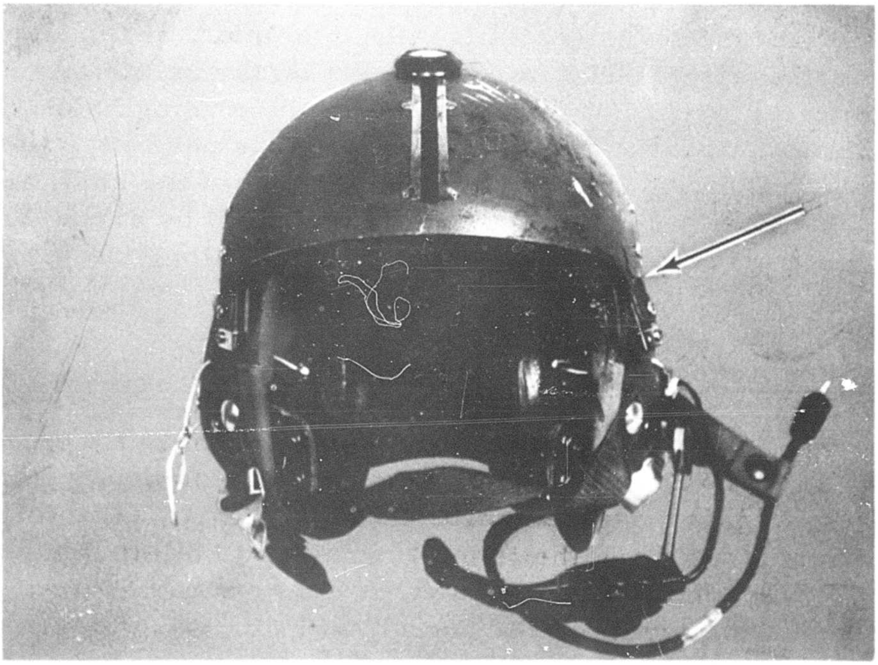

Figure 13. Front View of the Damaged Helmet.
The arrow indicates the point of impact on the visor housing.

allowed the helicopter support member to contact the skull directly at a single point in the left temporal area, where it produced a 3-centimeter laceration to the bone. There was no skull fracture.

Figures 6 and 7 show how the APH-5 has no energy absorbing capability in the latero-temporal area, as the styrofoam liner is cut away to accommodate the earphone installation. Because of the absence of liner in this area, no energy absorbing protection is afforded to the latero-temporal skull.

Thus, the point concentration of force on the visor keeper caused the spherical shell to bend inward and fracture, thus allowing the helicopter support structure to invade the confines of the helmet in an area in which there was no energy absorbing material present. This, then, allowed the head to contact the helicopter structure without significant attenuation of crash energy, and resulted in a fatal head injury.

Although the earphones take up most of the space in the lateral portion of the helmet, these offer no protection, as they consist of a hard metal core surrounded by bulky, soft foam rubber and have no energy absorbing capability; the hard core will only transmit energy to the temporal bone in an unattenuated manner.

Conclusions

1. The fatal injury was caused by direct transmission of energy to the head through the outer shell of an APH-5.

2. The construction of a metal visor keeper on the outside of the shell permitted concentration of impact forces onto one point of the skull.

3. The shell of the APH-5 flexed inward and fractured under point loading of force, allowing bottoming against the skull.

4. The protective properties of the APH-5 are not fully utilized because of the absence of energy absorbing material in the temporal areas.

Recommendations

1. Protuberances and attached articles should be avoided on the

surface of any helmet.

2. The materials and geometric configuration of the shell should be such that bottoming is eliminated.

3. Energy absorbing material should be incorporated in the latero-temporal portion of the helmet.

CASE B

Description of the Accident

The pilot was turning onto his final approach in preparation for a landing, when he noticed that he had overshot the runway. He tried to add power for a go-around, but the engine failed to respond and he was committed to force-land the aircraft in a wooded area.

The aircraft touched down on the main landing gear, which (progressively) collapsed. The aircraft then skidded into several trees, where it broke in two sections and the aft section burst into flames. The exact attitude at principal impact is not known; however, the aircraft was yawed to the right when it contacted a tree, producing a large dent in the fuselage, directly below the cockpit windshield side panel. The windshield side panel was shattered.

Helmet Damage

It was apparent that the pilot was thrown to the left during contact with a tree and that his head was far enough out of the cockpit to contact the tree with his helmet. It is quite possible that this contact was made at the same time that the cockpit was indented on the left side. Examination of the APH-5 helmet revealed that impact occurred at the front center (arrow 1, Figure 14), which split the sun-visor housing. The left half of the housing was torn off, the rivets being sheared at the attachment to the keeper (arrow 2, Figure 14).

Close examination of the helmet revealed wood splinters between the shell and the rim roll pad, confirming the strike against the tree (Figure 15, arrow).

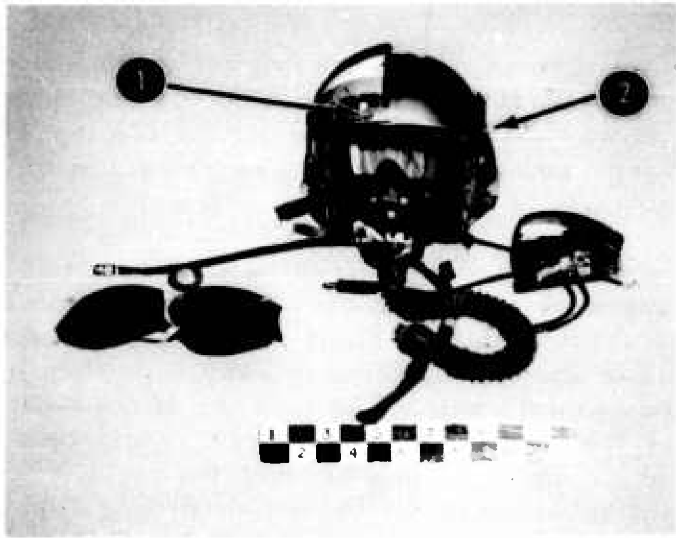

Figure 14. Front View of the Helmet, Showing the Impact Area. Arrow 1 points out the point of impact. Arrow 2 depicts the side attachment of the sun visor and sheared-off rivets.

Figure 15. Bottom View of the Pilot's Helmet.
The arrow depicts the wood splinters wedged between the outer shell and the rim lining.

Injury Analysis

The fatal frontal blow to the pilot's helmet and head caused contusion of the brain with generalized cerebral edema and multiple contusions of the head. It was not possible to estimate the forces involved; and since no autopsy was performed, the exact details of the brain injury are also unknown.

On the basis of the foregoing, it can only be assumed that the fatal injury was caused by a blow exceeding the design limits of the helmet. When the tree struck the helmet, it apparently contacted the frontal edge of the visor shield, breaking it away, and then impacted against the edge of the helmet shell. The manner of construction of the APH-5 offsets the energy absorbing liner up to 1 inch back from the edge of the shell. In this space is inserted a roll edge which is made of elastic foam rubber with no energy absorbing capability. Therefore, when the tree struck the edge of the shell, there was no energy absorbing material beneath to facilitate attenuation of applied forces. Not only does this dense elastic foam rubber absorb no energy, but it also causes magnification of forces due to the difference in the mass of the head and the helmet's creating excess G loads as the helmet rebounds from the impacted object, and the lag in head acceleration. (This is also true of the sizing pads.)

Conclusions

1. The fatal injuries to the pilot's head (cerebral contusion) were caused by a frontal impact of a tree while protected by an APH-5 helmet. Contact of the helmet with the tree occurred over the edge of the shell, under which no liner material was present.

2. The elastic foam-rubber edging provides no energy absorption and, further, allows magnification of forces.

Recommendations

1. The energy absorbing lining should be incorporated throughout the undersurface of the shell.

2. Use of elastic foam-rubber lining should be discontinued.

CASE C

Description of the Accident

The aircraft was occupied by a pilot in the left seat and an instructor pilot in the right seat for the purpose of a proficiency check. The aircraft flew a normal traffic pattern, after which hovering was practiced. The instructor pilot then asked for a demonstration of an aborted take-off. At an altitude of approximately 100 feet, the forward motion of the aircraft was stopped and rearward flight was initiated. During this portion of the flight, the tail pitched up and the aircraft dived into the ground at approximately a 65-degree angle and an undetermined amount of roll to the right. The accident was nonsurvivable because of post-crash fire.

Injury Analysis

The pilot, in the left seat, suffered, among other injuries, an 8-inch laceration under the chin, extending up to the floor of the mouth. The attending medical officer felt that the laceration under the chin was due to the fact that a loosely worn chin strap caused the helmet to come off at impact and that the strap tore into the fleshy area below the chin. Unfortunately, this helmet was partially consumed by fire, so that supporting evidence could not be obtained. It is known that the thin and pliable nylon chin strap of the APH-5 helmet can roll up and become a cord when under tension. It would appear, therefore, that injuries of this type could be prevented by using a chin strap made of a less pliable material, which would maintain a greater contact area and prevent cord-like action when under tension. A sleeve over the chin strap would also reduce the cutting action of the chin strap.

Conclusion

1. Although complete data on the pilot's helmet are not available, it is found that the chin injury was caused by the APH-5 chin strap.

2. The chin strap was probably adjusted loosely, and it rolled into a cord when the helmet was placed under stress.

Recommendation

The chin strap should be so constructed that it will not have the tendency to roll into a cord. The use of the sleeve would facilitate increasing the contact area of the strap and would thus reduce the cutting action. (This increase of contact area and softness of the sleeve would also make proper adjustment more comfortable).

CASE D

Description of the Accident

The aircraft was engaged in a search mission, when adverse weather conditions were encountered. The pilot apparently became dis-orientated and lost control of the aircraft, which resulted in a crash in a heavily wooded area. During the crash sequence, the aircraft struck a tree, which caused the pilot's seat to tear free. The seat, together with its occupant, were then ejected through the cockpit window..

Helmet Damage

The APH-5 helmet was severely damaged and was torn from the pilot's head. The chin strap fabric had failed at both end attachments; a complete delamination and tearing of the shell occurred from the leading edge adjacent to the right eye to a point above and behind the location of the right ear (Figure 16, arrow 1); an L-shaped complete delamination was noted adjacent to and posterior to the upper end of the left visor housing keeper (Figure 17, arrow 1); there was a rounded, depressed, delaminated area above and slightly to the rear of the left ear area (Figure 12, arrow 2).

The helmet liner showed fragmentation of the right section, with a crease-like deflection of 70 percent over the lower anterior half, encompassing thereby a very large area of this liner section. The center section of the liner appeared to be intact. The left section was severely fragmented, with multiple creases and a punctate area (in which the maximum deflection was 70 percent) which appeared to be beneath the rounded depression under the shell (Figure 18).

The chin strap failed at both ends: at the sewn seam on the right, and at the screw attachment on the left.

Injury Analysis

The injuries to the pilot's head were as follows: a compound comminuted depressed fracture of the right fronto-parietal skull; three

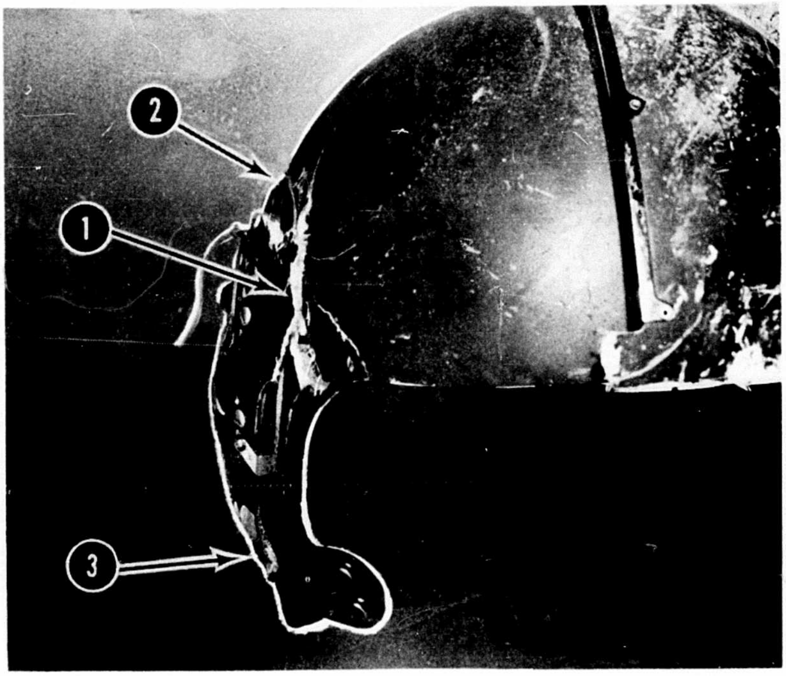

Figure 16. Right View of the Helmet, Showing Fracturing of the Shell and the Visor Shield Torn Away.

Note the deformation of the visor guide (arrow 2). Arrow 3 indicates where the chin strap failed at the sewn seam.

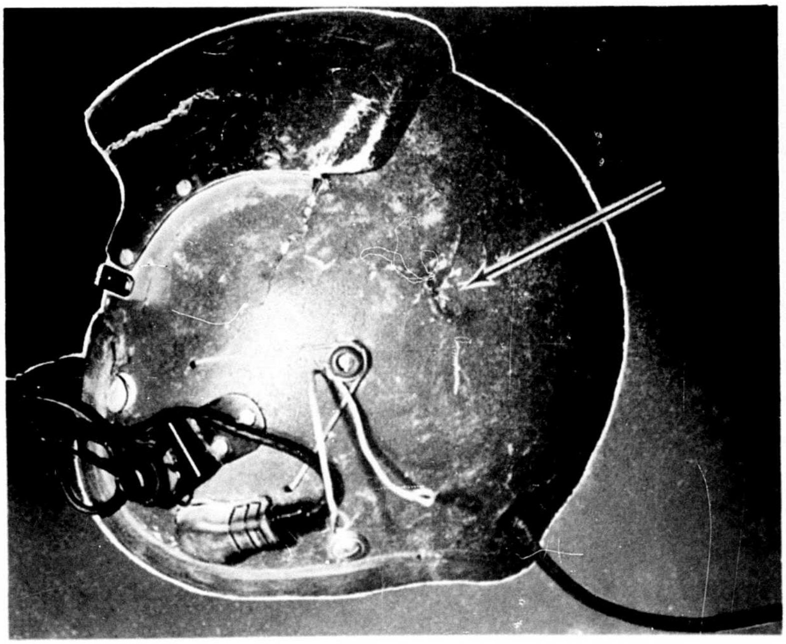

Figure 17. Left View of the Helmet, Showing Stellate Fracture With Penetration and Linear Fracture of Temporal Area.

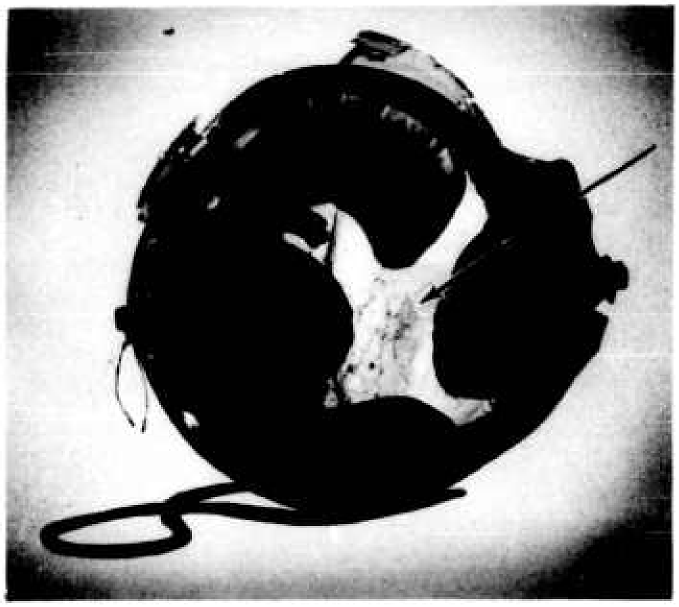

Figure 18. Left Internal View of the Helmet, Showing the Punctate Area Under the Rounded Depression of the Shell, With Fragmentation of the Liner Section due to Penetration of Foreign Object.

8-centimeter parallel lacerations from the left forehead to the angle of the left mandible; a superficial abrasion under the chin; and probable fracture of the neck. The body of the pilot was removed from the scene, embalmed, and buried before complete medical observations could be made by X-ray or autopsy. It was, therefore, not possible to make an accurate and complete evaluation of the correlation between the injuries and the APH-5 helmet damage.

A careful study of the helmet was made by the Snell Memorial Foundation, Inc., in Sacramento, California. It was found that the damage to the shell and liner constituted energy transfers that were quite sufficient to have provided the lethal effects to the skull. The amount of deflection of the liner and the wide area over which this deflection occurred indicated tremendous forces involved in this accident.

It can be seen in Figures 16 and 17 that the delaminations and tears in the shell are in close proximity of the eye-shield housing keeper. Further, arrow 2 in Figure 16 shows where the helmet snagged on aircraft structure, which is also shown in Figure 19. This snagging

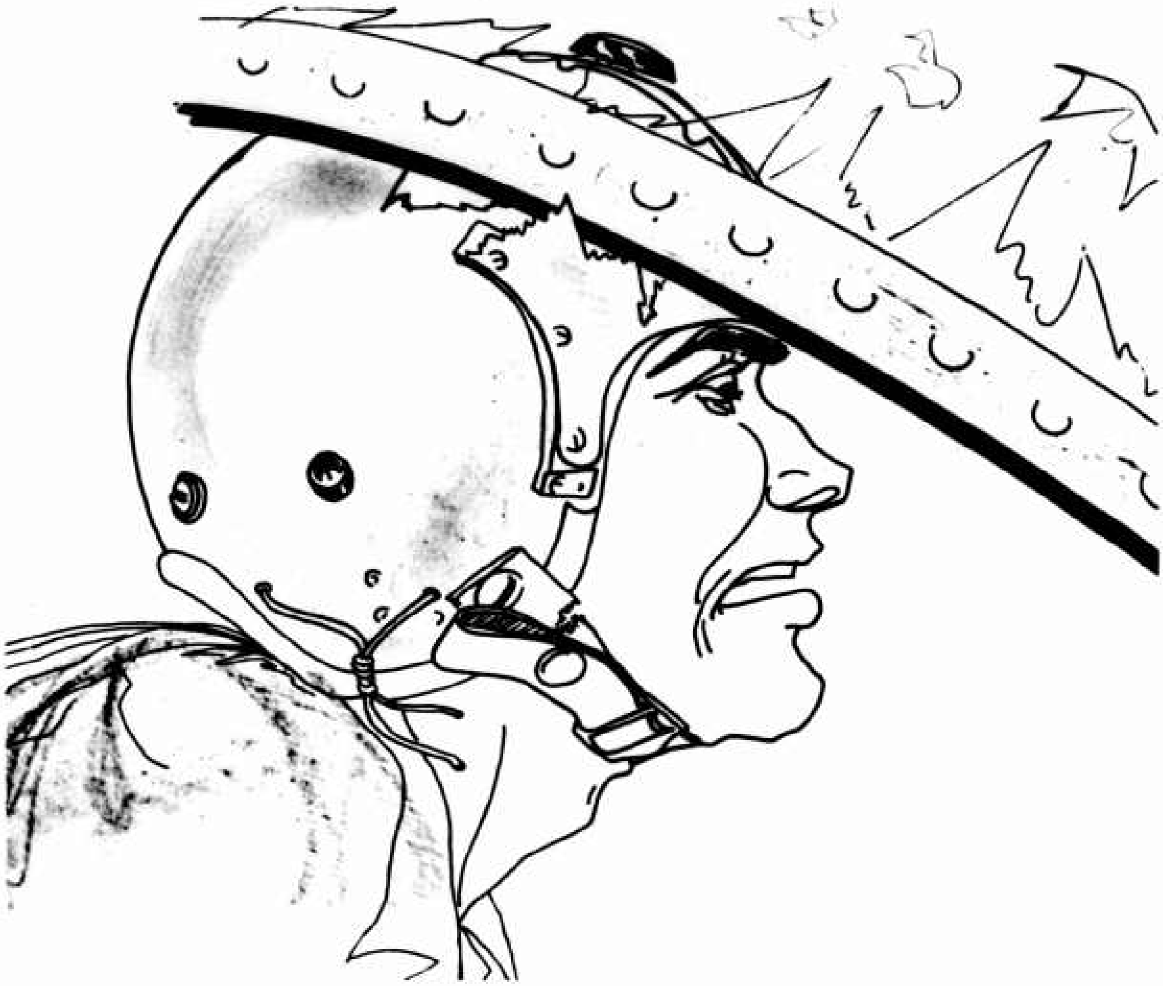

Figure 19. Illustration of Pilot's Helmet Visor Keeper Snagging on the Window Structure.

caused severe lateral torsion of the helmet and head, producing the tearing of the shell and probable fracture of the neck. Failures of the helmet shell in this area are frequently observed in helmets subjected to impact forces and are caused by the concentration of force on the small area of the keeper and other protuberances. It appears that any helmet design which utilizes rigid projections on the helmet surface and prevents the surface from being essentially smooth and clean is a less than satisfactory design.

Retention of the helmet is considered to be a problem in accidents, as statistics bear out the fact that the APH-5 is often forcibly removed from the head in violent decelerations. However, the main reason for helmet separation evidently is retention system failure. Figure 16 shows the failure point of the chin strap at the sewn seam, and Figure 17 shows where the left end is no longer attached at its screw anchorage point. Although it is realized that extraordinary forces were involved in this accident, this is one of the several accident cases where the chin strap had failed in essentially the same location.

Conclusions

1. Fatal head and neck injuries occurred because of transmission of forces to the pilot's head by snagging of the visor keeper and because of loss of the helmet due to retention system failure.

2. The styrofoam liner was deformed to 70 percent over much of the anterior part of the helmet; thus its energy absorption capability was expended, and forces were transmitted unattenuated.

3. The visor keeper snagged on aircraft structure and caused severe, sudden rotation of head and neck.

4. The retention system failed and allowed the helmet to separate from the pilot's head; this left his head unprotected for the remaining of the impact sequence.

Recommendations

1. Stronger materials and geometric configuration which will not easily allow fracturing or bottoming should be utilized for the shell.

2. More energy absorption liner material should be utilized in the anterior portion of the helmet.

3. Protruding snag points and stress concentration points should be avoided or eliminated.

4. The retention system should be increased in strength.

CASE E

Description of the Accident

The aircraft was crashed under closely controlled and monitored conditions in an experimental crash test which re-created a typical accident approximating an unsuccessful (attempt to attain) autorotation from a low-altitude power failure. The aircraft was fully instrumented and photographic coverage was provided. An anthropomorphic dummy was placed in the pilot's seat and was fitted with an APH-5 crash helmet.

The aircraft was dropped 28 feet from the boom of a crane moving at 26 mph. The aircraft impacted in a three-point attitude, with a slight roll and yaw to the left, onto a hard-surfaced runway.

At impact, the overhead structure of the cockpit, weighted with the forward rotor transmission, collapsed downward and thus reduced the vertical dimension of the cockpit. The pilot dummy was then compressed between the lowering overhead structure and the seat, which also failed.

Helmet Damage

The impact on the helmet by the overhead cockpit structure was sufficient to cause the following damage to the APH 5 helmet: an oblique linear abrasion over the right frontal area of the visor housing; a small portion of the housing above this abrasion was fragmented and broken off at the upper edge. A linear partial delamination of the fiberglass shell occurred on the coronal region, and a stellate punctate indentation with delamination was produced adjacent to and to the right of the coronal abrasion. This indentation showed a complete delamination.

There was a 3-by-4-centimeter area of compression in the coronal region of the left liner section, with a maximum permanent deformation of approximately 40 percent of original thickness. The center section of the liner showed approximately 50 percent deformation in the frontal area along the right margin. A crease was noted in the coronal region underlying the delamination of the shell, with approximately 40 percent deformation of the liner material. The right section of the liner was severely damaged over its anterior two-thirds, including the coronal region. There was some actual fragmentation of the liner in the crown, and the maximum deformation was 70 percent over a 5-by-11-centimeter area. Figure 20 is a photo of the damaged helmet.

Injury Analysis

Damage to an anthropomorphic dummy cannot be considered to be comparable to injury to human tissue. Therefore, in evaluating the injury-producing forces that the dummy's head was exposed to, it is necessary to relate the damage done to the helmet in the test to damage done to helmets in the field, and then to work back to the accelerations measured in the dummy's head to determine the expected injury.

In order to determine the accelerations transmitted to the whole head of the dummy, accelerometers were securely mounted on plates in the cranial vault in the lateral, longitudinal, and vertical axes; the accelerations imparted were recorded on an oscillograph.

The peak accelerations obtained were:

Vertical	+ 78 G, duration of .037 sec.
	− 25 G, duration of .027 sec.
Longitudinal	+ 39 G, duration of .022 sec.
	− 38 G, duration of .028 sec.
Lateral	+ 33 G, duration of .027 sec.

These measurements represent accelerations imparted to the whole head.

Because of the vertebral support from below and the contact of the cockpit structure from above, the dummy's head and helmet experienced a mechanical crushing-type injury with relatively moderate accelerations. These accelerations have been known to be of survivable levels. Survivors of free-fall cases have disclosed accelerations of whole heads in the range of 200 G for a duration of .015 - .03 second (Reference 15).

However, fractures and brain damage cannot be related simply to whole head acceleration, as the failure of the helmet shell allowed more focal concentration of forces to occur under the areas of failure. Distribution of force over a maximum area of liner, allowing a maximum dissipation of energy through a greater volume reduction of energy absorbing material, was lost. Only the energy absorption material in the immediate failure sites was crushed to its maximum of 70 percent, at which amount of deformation it no longer has any

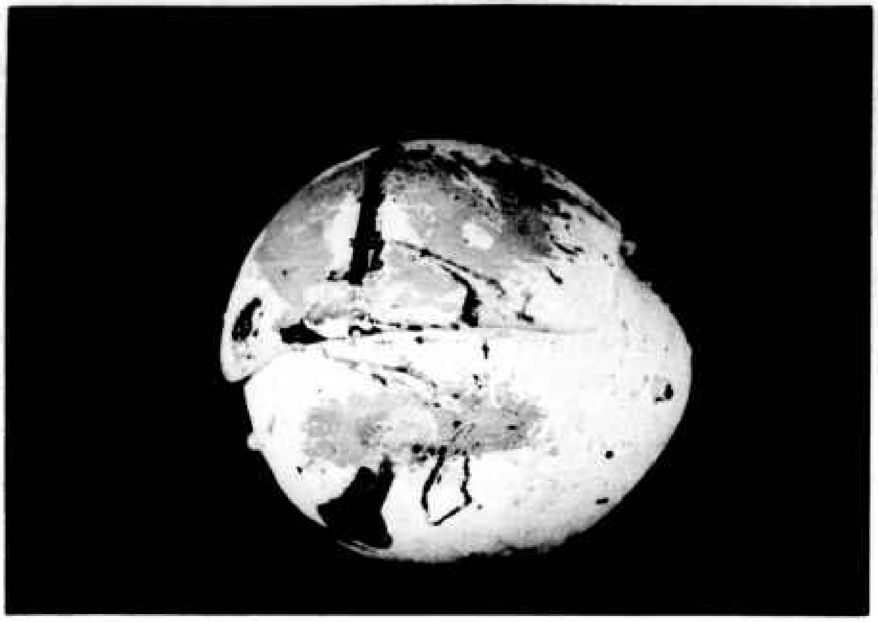

Figure 20. Top View of APH-5, Showing Damage to Visor Shield and Crown.

capability for energy dissipation and then transmits force as a solid elastic material. Therefore, the helmet and the section of the overhead structure of the cockpit on which it impacted were given to the Snell Memorial Foundation, Inc., for analysis of the magnitude of force involved. In order to approximate the impact conditions, a striking bob face was made from a portion of the structure used in the drop test. This striker was used in a test on a new and unused APH-5 helmet. The Snell Memorial Foundation reported the following information:

> "A comparison of the amount of damage done to the shells and more particularly to the non-resilient liners of these two helmets would lead us to believe that the amount of energy transferred in the test drop to the dummy's head would have been quite sufficient to have been lethal to a human under similar circumstances. We are certain that the localized accelerations developed at points beneath the sites of impact were well over 450 G's. Added to this, the area of involvement noted in the test drop helmet was considerably greater than that which we have seen in field accidents of fatal nature."

Thus, it is apparent that failure of the helmet shell allowed transmission of force focally in sufficient magnitude to be fatal, while the overall acceleration of the total head did not exceed fatal limits. This points out very graphically the importance of the need for adequate distribution of force over the maximal contours of the head in line with the direction of impact.

Conclusions

1. The whole head accelerations, as measured in the cranial cavity of the dummy, were well within survivable limits.

2. The local accelerations at the points of helmet shell and liner failure exceeded the limits of human tolerance and would have caused fatal injuries.

Recommendations

1. Maximal distribution of forces should be achieved by utilizing rigid, tensile and geometrically strong materials.

2. Maximal amount of force attenuation should be achieved by utilizing the greatest amount of energy absorbing liner consistent with weight requirements.

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Report is made of crash injury evaluation of the U.S. Army APH-5 helmet, observations of problems encountered from an injury prevention viewpoint and concepts on how these injuries could possibly be reduced.

<u>UNCLASSIFIED</u>

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